

From the Higgs to the top: Couplings and Rare Decays

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Within the Standard Model the Higgs couplings to fermions and gauge bosons, as function of the particle mass, are predicted to lay on a single line. However, new patterns appear in multi-Higgs models that employ the Froggatt-Nielsen mechanism, where the diagonal couplings could lay on different lines and flavor-violating Higgs couplings could appear too. These aspects are studied for a specific model with 3+1 Higgs doublets and a singlet FN field. Constraints on the model are derived from the Higgs search at LHC, and some remarks are presented on their implications for the rare top and Higgs decay, $t \rightarrow ch$ and $h \rightarrow \tau\mu$.

I. INTRODUCTION

The discovery of a Higgs-like particle with $m_h = 125 - 126$ GeV at the LHC [1, 2], has verified the mechanism of Electro-Weak symmetry breaking of the Standard Model (SM) [3]. Current measurements of the spin, parity, and couplings of the Higgs, seem consistent with the SM. On the other hand, several scenarios for Physics Beyond the SM (PBSM) have been proposed to address some of its open problems, such as hierarchy, flavor, unification, etc [4, 5]. So far, the LHC bounds on its scale (Λ) are entering into the multi-TeV range, which could mean $\Lambda \gg v = 246$ GeV. A more solid conclusion needs to wait for the next LHC run, with higher energy and luminosity. Many papers have been devoted to study the LHC implications for the Higgs couplings, for instance in [6, 7]. The couplings of the Higgs particle to a pair of massive gauge bosons or fermions, are proportional to the particle mass. However, the LHC has tested only a few of these couplings, i.e. the ones with the heaviest SM fermions and W, Z . Non-standard Higgs couplings, including the flavor violating (FV) ones, are predicted in many models of physics beyond the SM, for instance in the general multi-Higgs models [8, 9] and SUSY [33].

Many ideas have been proposed to adress the flavor problem [10], for instance: Textures and GUT-inspired relations, flavor symmetries and radiative generation. Within the flavor symmetry approach, the Froggatt-Nielsen mechanism assumes that above some scale M_F , such symmetry forbids the appearance of the Yukawa couplings; SM fermions are charged under this symmetry (which could be of Abelian type $U(1)_F$). However, the Yukawa matrices can arise through non-renormalizable operators. The Higgs spectrum of these models could include a light and heavy Higgs boson. In these models the diagonal flavor conserving (FC) couplings of the light SM-like Higgs boson could deviate from SM, while flavor violating (FV) couplings could be induced at small rates too. Within the SM, the FC Higgs couplings to fermions and gauge bosons, as function of the particle mass, lay on a single straight line. However, in multi-Higgs models, they could lay on distinct lines. As illustrated in Figure 1, the scalar spectrum could include:

- i) A lightest state that should be identified with the SM-like Higgs boson. One expects, the appearance of small deviations from SM predictions for the diagonal Higgs-fermion couplings and suppressed FV couplings.
- ii) States with Flavon-dominated composition, which could provide the more radical signature of the models under consideration. The observation of these signals depends on the flavon scale, and could at the reach of the LHC reach if such scale were about $O(1)$ TeV.
- iii) Heavy Higgs bosons which could have large mixing with flavons, and thus deviate significantly from SM expectations for FV couplings, that could also be searched at LHC.

II. HIGGS COUPLINGS WITHIN A 3+1 HIGGS MODEL

Thus, we shall consider a 3+1-Higgs doublet model, denoted as $\Phi_0, \Phi_1, \Phi_2, \Phi_3$. The Φ_1 gives masses to up-type quarks, while Φ_2 and Φ_3 give masses to d-type quarks and leptons, respectively. We shall impose a discrete symmetry in such a way that one doublet (Φ_0) is of the inert-type, and therefore contains a Dark matter condidate [12]. Furthermore, we shall also include Froggatt-Nielsen scalar field (SM singlet S). The possibility of having light flavon fields was studied in ref. [11], and more recently in [13, 14]. The Yukawa lagrangian is

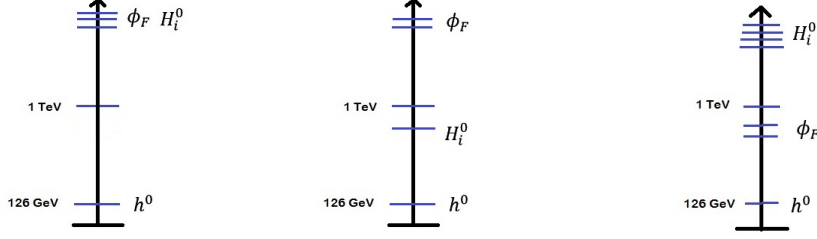


FIG. 1: The Higgs and flavon spectrum in multi-Higgs models.

given by:

$$\mathcal{L}_Y = \rho_{ij}^u \left(\frac{S}{\Lambda_F}\right)^{n_{ij}} \bar{Q}_i d_j \tilde{\Phi}_1 + \rho_{ij}^d \left(\frac{S}{\Lambda_F}\right)^{p_{ij}} \bar{Q}_i u_j \Phi_2 + \rho_{ij}^l \left(\frac{S}{\Lambda_F}\right)^{q_{ij}} \bar{L}_i l_j \Phi_3 + h.c. \quad (1)$$

where n, p, q denote the charges of each fermion type under an Abelian flavor symmetry, which will help to explain the fermion mass hierarchy. The flavon field S is assumed to have flavor charge equal to -1, such that \mathcal{L}_Y is $U(1)_F$ -invariant. Then, Yukawa couplings arise after the spontaneous breaking of the flavor symmetry, i.e. $\lambda_x = (\frac{\langle S \rangle}{\Lambda_F})^{n_x}$, where $\langle S \rangle$ denotes the flavon vacuum expectation value, while M_F denotes the heavy mass scale, which represents the mass of heavy fields that transmit such symmetry breaking to the quarks and leptons.

The Higgs and Flavon fields are written in terms of mass eigenstates, through the rotation O^T (4×4):

$$\begin{aligned} Re\Phi_i^0 &= O_{i1}^T h_1^0 + O_{i2}^T H_2^0 + O_{i3}^T H_3^0 + O_{i4}^T H_F^0 \\ ReS &= O_{41}^T h_1^0 + O_{42}^T H_2^0 + O_{43}^T H_3^0 + O_{44}^T H_F^0 \end{aligned} \quad (2)$$

Furthermore, as the vev's must satisfy: $v_1^2 + v_2^2 + v_3^2 = v^2$, with $v = 246$ GeV, we find convenient to use spherical coordinates to express each vev (v_i) in terms of the total vev v and the angles β_1 and β_2 , as shown in figure 2, namely: $v_1 = v \cos \beta_1$, $v_2 = v \sin \beta_1 \cos \beta_2$ and $v_3 = v \sin \beta_1 \sin \beta_2$.

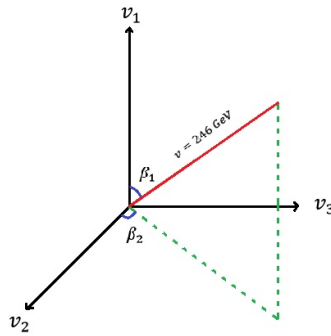


FIG. 2: The Higgs vevs in spherical coordinates.

Thus, for the lightest Higgs state ($h_1^0 = h^0$), one gets finally the following interaction lagrangian for the Higgs-fermion couplings,

$$\mathcal{L}_Y = \left[\frac{\eta^u}{v} \bar{U} M_u U + \frac{\eta^d}{v} \bar{D} M_d D + \frac{\eta^l}{v} \bar{L} M_l L + \kappa^u \bar{U}_i \tilde{Z}^u U_j + \kappa^d \bar{D}_i \tilde{Z}^d D_j + \kappa^l \bar{L}_i \tilde{Z}^l L_j \right] h^0 \quad (3)$$

where: $\eta^u = O_{11}^T / \cos \beta_1$, $\eta^d = O_{21}^T / \sin \beta_1 \cos \beta_2$, $\eta^l = O_{31}^T / \sin \beta_1 \sin \beta_2$, describe the strength of the flavor-diagonal Higgs couplings. While the FV Higgs couplings are described by the parameters: $\kappa^u = \frac{v}{u} O_{41}^T \cos \beta_1$, $\kappa^d = \frac{v}{u} O_{41}^T \sin \beta_1 \cos \beta_2$, $\kappa^l = \frac{v}{u} O_{41}^T \cos \beta_1 \sin \beta_2$.

Besides the Yukawa couplings, we also need to specify the Higgs couplings with vector bosons, which is written as $g_{hVV} = \chi_V g_{hVV}^{sm}$, with the factor χ_V given as:

$$\begin{aligned}\chi_V &= \frac{v_1}{v} O_{11}^T + \frac{v_2}{v} O_{21}^T + \frac{v_3}{v} O_{31}^T \\ &= \cos \beta_1 O_{11}^T + \sin \beta_1 \cos \beta_2 O_{21}^T + \sin \beta_1 \sin \beta_2 O_{31}^T\end{aligned}\quad (4)$$

It is interesting to note that the coupling χ_V can be written in terms of the FC fermionic couplings, which can be seen as a type of sum rule, i.e.

$$\chi_V = \cos^2 \beta_1 \eta^u + \sin^2 \beta_1 \cos^2 \beta_2 \eta^d + \sin^2 \beta_1 \sin^2 \beta_2 \eta^l \quad (5)$$

Moreover, since the Higgs couplings to first generation quarks and leptons is highly suppressed, in order to study the FV Higgs coupling, which depends on the matrices \tilde{Z}^f , we shall consider the 2-3 family sub-system. Namely, for up quarks the Z -matrix (in mass eigenstate basis), is given by:

$$\tilde{Z}^u = \begin{pmatrix} Y_{22}^u & Y_{23}^u \\ Y_{23}^u & 2s_u Y_{23}^u \end{pmatrix} \quad (6)$$

and similarly for d-quarks and leptons. We find a relation among the parameters, such that we can express the $\rho_{ij}^{u,d}$'s in terms of the ratios of masses and the CKM angle $V_{cb} \simeq s_{23}$. Namely, we define: $r_u = m_c/m_t$, $r_d = m_s/m_b$, and $r_1^u = Y_{22}^u/Y_{33}^u$, $r_2^u = Y_{23}^u/Y_{33}^u$. Similarly: $r_1^d = Y_{22}^d/Y_{33}^d$, $r_2^d = Y_{23}^d/Y_{33}^d$. Within this approximation we have: $\tilde{Y}_{33}^f \simeq Y_{33}^f$ for $f = u, d$. Then, $r_1^f = r_f + r_2^f$, and the ratios of Yukawas must satisfy the following relation:

$$r_2^u = r_2^d \frac{1 + r_d}{1 + r_u} - \frac{s_{23}}{1 + r_u} \quad (7)$$

Thus, in order to study the predictions of our model, we need to specify the vevs v_i and the rotation matrix for Higgs particles (O_{ij}). For the 2HDM (see for instance [15]), LHC Higgs data favors both decoupling and alignment solutions, namely both $\tan \beta \simeq 1$ and $\tan \beta \gg 1$ are acceptable solutions. Thus, for the vev's we leave β_1 as free parameter, then explore the following cases:

- (VEV1) We can take first $v_2 = v_3$, which in spherical coordinates, means: $\beta_2 = \frac{\pi}{4}$,
- (VEV2) We also consider vevs with $v_2 < v_3$, for which we take: $\beta_2 = \frac{\pi}{3}$,
- (VEV2) We also consider vevs with $v_2 > v_3$, for which we take: $\beta_2 = \frac{\pi}{6}$,

Then, for the rotation matrix O of real components of scalar fields, we can identify several interesting scenario where the 126-Higgs is lighter than the heavy Higgs particles and the flavons, i.e. $m_h < m_{H_i} \simeq m_{H_F}$, which have masses of order TeV. Here, we shall consider a special sub-case, namely we shall assume that $O_{11}^T > O_{i1}^T$, and will use the orthogonality relation for the rotation matrix O , in order to relate the parameters, namely: $(O_{11}^T)^2 + (O_{21}^T)^2 + (O_{31}^T)^2 + (O_{41}^T)^2 = 1$. Furthermore, assuming $O_{i1}^T \simeq O_{j1}^T$ (for $i \neq j$) one has $O_{j1}^T = \sqrt{\frac{1 - (O_{11}^T)^2}{3}}$.

III. FLAVOR CONSERVING HIGGS COUPLINGS AT LHC

LHC data on Higgs boson has been used to derive bounds on the Higgs couplings, i.e. deviation from the SM, which are defined as: $g_{hXX} = g_{hXX}^{sm}(1 + \epsilon_X)$, where $\eta^X = 1 + \epsilon_X$. A complete analysis is done in ref. [7]; for fermions, they obtain the allowed values: $\epsilon_t = -0.21 \pm 0.23$, $\epsilon_b = -0.19 \pm 0.3$, $\epsilon_\tau = 0 \pm 0.18$; while for W (Z) bosons they find: $\epsilon_W = -0.15 \pm 0.14$, $\epsilon_Z = -0.01 \pm 0.13$.

An extensive analysis of parameters satisfying these bounds will be presented elsewhere, with detailed numerical scans; here we shall pick a few specific points in parameter space, which satisfy the LHC bounds, and will help us to understand qualitatively the behaviour of the model. These points will also be used in the next section in our analysis of FCNC top decays. Thus, we show in figure 3-6 the predictions for each of these parameters, as function of the angle β_1 , for the case with $\beta_2 = \frac{\pi}{3}$, $\frac{\pi}{4}$, $\frac{\pi}{6}$, and for $O_{11} = 0.5, 0.75, 0.9$. We can see that it is possible to satisfy these bounds for all the ϵ 's.

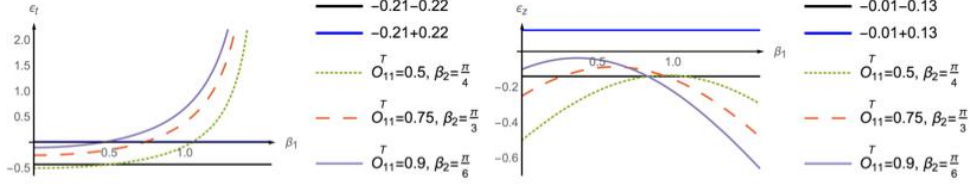


FIG. 3: Higgs coupling factors ϵ_t and ϵ_z for the parameters of set 1. The horizontal lines are the experimental limits on these factors.

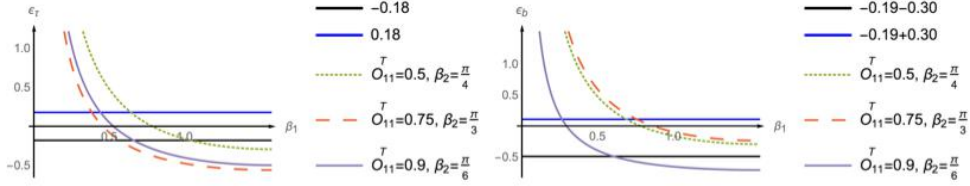


FIG. 4: Higgs coupling factors ϵ_τ and ϵ_b for the parameters of set 1. The horizontal lines are the experimental limits on these factors.

One specific point, in agreement with all data, is : $\beta_1 = 0.5$ with $O_{11} = 0.9$ and $\beta_2 = \frac{\pi}{6}$. For these values we have: $\eta^u = 1.03$, $\eta^d = 0.6$ and $\eta^l = 1.04$ and $\chi_v = 0.96$. This shows that h behaves very much SM-like, except for the coupling with d-type quarks. Then, using these values we can plot the Higgs-fermion coupling as function of the mass, as shown in figure 2. We can see that the couplings for each fermion type lay on different lines, which could be distinguished from the SM (Black line). Future measurements of these couplings at LHC Run2, ILC or FCC will help us in order to discriminate between our model and the SM.

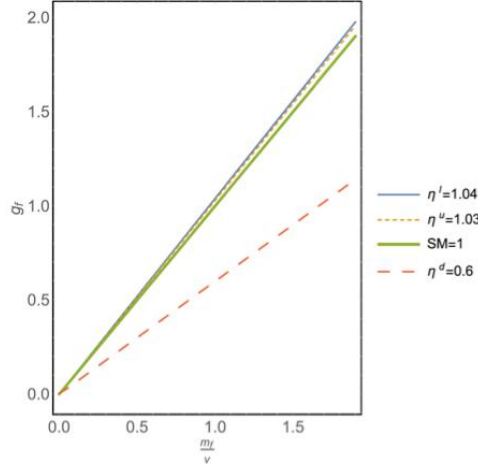


FIG. 5: The Higgs-fermion coupling factors as function of mass, for parameters defined in the text. SM case (Black), up-type quarks (red), d-type quarks (blue), charged leptons (green).

We also find that the corrections contained in the factors $\kappa^f \tilde{Z}^f$, will not change significantly the above discussion for the top quark-Higgs couplings. However, the Higgs coupling with the lighter fermions ($b\bar{b}$, $c\bar{c}$, $\tau^+\tau^-$), could be measured at next-linear collider (NLC) with a precision of a few percent, and it will be possible to test these effects. The corrections to the coupling $h\bar{b}b$, could modify the dominant decay of the light Higgs, as well as the associated production of the Higgs with b-quark pairs [16].

We shall consider the following sample values: $r_d^2 = 0.05, 0.1, 0.3$, and also assume: $\cos\beta_1 \simeq 1$, then table 1 shows the values of the entries for the \tilde{Z}^u matrix for the 2nd-3rd family case. We choose to focus on the up-quark sector, because we want to get an estimate for the most relevant predictions of the model, which we believe is related with the top quark physics, and in particular for the decay $t \rightarrow c + h$. For the specific point in parameter space, presented in previous section: $\beta_1 = 0.5$ with $O_{11} = 0.9$ and $\beta_2 = \frac{\pi}{6}$. which is in agreement with LHC data, we obtain the following value $\kappa^u = 0.23 \frac{v}{u}$.

Scenario	u[TeV]	$\kappa^u \times \tilde{Z}_{23}$	$B.R.(t \rightarrow ch)$
X1	0.5	1.2×10^{-4}	8.6×10^{-9}
X2	1	6.1×10^{-5}	2.2×10^{-9}
X3	10	6.1×10^{-6}	2.2×10^{-11}
Y1	0.5	6.9×10^{-3}	2.7×10^{-5}
Y2	1	3.4×10^{-3}	6.8×10^{-6}
Y3	10	3.4×10^{-4}	6.8×10^{-8}
Z1	0.5	2.9×10^{-2}	4.8×10^{-4}
Z2	1	1.4×10^{-2}	1.2×10^{-4}
Z3	10	1.4×10^{-3}	1.2×10^{-6}

TABLE I: The factor $\kappa^u \times \tilde{Z}_{23}^u$ and Branching ratios for $t \rightarrow ch$

IV. THE FCNC DECAY $t \rightarrow ch$

The top radiative decay $t \rightarrow c + \gamma$ was first calculated in [17], followed by ref. [18] which presented the complete calculations of the FCNC modes $t \rightarrow cX$ ($X = \gamma, g, Z, h$); for corrections to SM results for $t \rightarrow ch$ and SUSY results see also: [19, 20]. The 3-body FCNC decays modes $t \rightarrow cW^+W^-(ZZ, \gamma\gamma)$, were presented in ref. [21, 22], while the mode $t \rightarrow c\ell^-\ell^+$ was discussed recently in [23, 24]. The 4-body decay $t \rightarrow bW\ell^-\ell^+$ was also studied recently [25]. Here we shall focus on the mode $t \rightarrow ch$, which can reach large BR's. The decay with for $t \rightarrow ch$ within our model is given by:

$$\Gamma(t \rightarrow ch) = \frac{m_t}{6\pi} |\kappa^u \tilde{Z}_{23}|^2 \quad (8)$$

Using the value $\Gamma(t \rightarrow b + W) \simeq 1.5$ GeV, we obtain: $BR(t \rightarrow ch) = 0.58 |\kappa^u \tilde{Z}_{23}|^2$. For $v/u = 0.25$, and one finds that the B.R. could reach a value $BR \simeq 1.5 \times 10^{-4}$, which could be tested at LHC [26]. Values of BR for other choices of parameters are shown in table 1.

V. THE LFV DECAY $h \rightarrow \tau\mu$

Another interesting probe of FV Higgs couplings is provided by the decay $h \rightarrow \tau\mu$, which was initially studied in refs. [27, 28]. Subsequent studies on detectability of the signal appeared soon after [29–31]. Precise loop calculations with massive neutrinos, SUSY and other models appeared in [32–35]. The recent search for this decay at LHC [37], have resulted in a bound for the corresponding branching ratio of order $B.r.(h \rightarrow \tau\mu) < 1.51 \times 10^{-2}$ at 95% c.l.. Furthermore, given that the best fit to the data gives $B.r.(h \rightarrow \tau\mu) = 0.84_{-0.37}^{+0.39} \times 10^{-2}$, many more papers have appeared recently, trying to explain this result [38]. The search for this LFV Higgs decay could be one great opportunity to find new physics at the LHC RunII.

VI. CONCLUSIONS AND OUTLOOK

We have studied the Higgs couplings, within a model with 3+1 Higgs doublets, where the masses for each fermion type, arise from a different Higgs doublet. This model also includes mixing of the Higgs doublets with a Flavon field, which generates the Yukawa hierarchies and induces Flavor-violating Higgs couplings at acceptable rates. Constraints on these couplings, derived from Higgs search at LHC, and their implications for FCNC top decay $t \rightarrow ch$, were discussed too. We find that this mode could reach a BR of order 10^{-4} , which could be studied at LHC. In the down-quark and lepton sectors, there are also interesting aspects to study in the future, such as the rates for rare b-decays. or the decay $h \rightarrow \tau\mu$, which can be induced at rates that could be detected at future colliders.

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